Near-Earth Asteroid Rendezvous Mission

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We propose an extremely quick and inexpensive asteroid rendezvous mission in near-Earth space using existing off-the-shelf technology which would allow nations of the world to start learning about cooperatively detecting, characterizing, and mitigating approaching asteroid impact threats. A solid-fueled space launch vehicle would be on standby status with a small, smart, lightweight spacecraft in the payload compartment. Once notified by an electronically connected net of worldwide astronomers of an asteroid on a verified close approach to Earth, the rocket would be quickly prepared and sent on a rendezvous trajectory with the approaching body. The spacecraft would conduct either an instrumented fly-by or a penetration of the body, while collecting and transmitting real-time scientific data. Radars, telescopes, and antennas on Earth would observe the rendezvous and gather data from the encounter. Technical details of the rendezvous mission are given, along with the scientific and mission-specific data to be collected and the types and levels of understanding to be derived from each. Three-dimensional calculations of an example penetration mission using the SPH hydrocode are also shown.

Introduction

Compelling evidence of a catastrophic asteroid impact on the Earth 65 million years ago (Alvarez et al., 1980 and Sharpton and Ward, 1990) has given rise to international discussions about the probability and prevention of future impacts. As a result of several recent near-misses (Morrison, 1992 and Scotti et al., 1991) and the comet Shoemaker Levy-9 impact of Jupiter in July 1994, considerable international attention has focused on defining the impact threat and determining potential hazard mitigation defense schemes for the protection of Earth against planetesimal impacts (Tedeschi, 1994). Protection of Earth from comet and asteroid impacts is something that has been discussed over the past decade or so, but which has never been seriously considered until recently. This paper offers a proposed approach for nations to learn how to conduct a cooperative, quick, low-cost NEO rendezvous mission.

We assume that rocket-delivered mitigation technologies will be the defense option of choice in the near-term, and ignore the promising potential of longer-term mitigation technologies, like directed energy mitigation technologies beamed directly from Earth to an approaching body. Initial studies indicate that hypervelocity impact is one of several favorable schemes for mitigating the possibility of Earth-impact by such bodies (Canavan et al., 1992; Tedeschi, 1995; and Wood et al., 1995). A desirable characteristic for a kinetic energy impact would be to deflect the approaching body into a new, non-threatening trajectory by a momentum transfer process. However, fragmentation of the body into numerous pieces is to be avoided since some of the resultant debris might still be on an Earth-impacting trajectory, although this may be a desirable approach against smaller NEOs, or the option of last resort if the warning time is short and no other mitigation options exist. See Tedeschi, 1995 and Wood et al., 1995 for more details on the applications of kinetic energy to deflect or fragment NEOs.

While there are some data on the fragmentation of Earth-derived planetesimal-type materials, e.g., basaltic rocks (Fujiwara et al., 1977) and ice (Kawakami et al., 1983), literally nowhere can one find experimental data on momentum deposition into such materials due to hypervelocity kinetic energy impacts. Tedeschi et al., 1994 contains world-unique data in this regard. Of course, planetary geophysicists have been studying this type impact phenomena for years, but they can only infer the full-scale response of large asteroids to massive kinetic energy impacts (Housen and Holsapple, 1990). Simulating the macroscopic change in momentum of such bodies is difficult to do using modern shock-physics computational codes, e.g., hydrocodes, mainly due to inherent numerical limitations (Anderson, 1987). Therefore, a critical need exists to not only obtain well-c haracterized hypervelocity impact test data from actual sub-scale NEO materials or NEO material analogs for code calibration purposes, but also to conduct asteroid impact experiments in space to affect full-scale target response observational opportunities. There is no other apparent way to obtain detailed in-depth material property data, energy coupling, and structural response characteristics of NEO bodies due to kinetic energy impacts, or any other mitigation technology for that matter, in the absence of full-scale rendezvous tests. Spacecraft flybys can collect information on NEO dynamic, geometric, and surface mineralogical characteristics. Spacecraft sample return missions provide opportunities to additionally characterize surface and nominal subsurface materials, while seismic probings would provide some additional detail on first-order internal structural characteristics, but not about how the body would actually respond to an actual impact. Large-scale testing in space appears to be the only alternative. Some would argue that every NEO target may be different. This may be so, but having one or two, well-characterized, full-scale data points would be much preferred.

The scientific endeavors associated with geophysical planetary evolution would also benefit directly from the proposed NEO rendezvous mission. Hypervelocity impact interactions and their related catastrophic effects have traditionally been invoked as the major plausible mechanism that determines the mass spectra and velocity dispersions during planetary accretion and fragmentation (Hartmann, 1978). Modeling such impact interactions can be very complicated, especially when either the target or impactor are composed of natural materials which in many cases are inhomogeneous assemblages of minerals with faults, inclusions, grain and phase boundaries, and other imperfections which complicate the material response. The response of such materials to hypervelocity impact spans a wide range of material behavior, ranging from high impact temperatures and pressures, where hydrodynamic motion and thermodynamic effects predominate, to the low pressure regions where the mechanical properties dominate the process. In order to simulate such processes using sophisticated computer models it becomes necessary to understand the fragmentation effects of hypervelocity impact on related inhomogeneous targets through experimentation over a range of loading conditions, velocities, and target and projectile scale and materials. Results from such experiments can then be used to test and validate computer models for the simulation of planetary interaction processes.

Why a quick asteroid rendezvous mission?

The end of the Cold War has allowed some nations of the world to focus more attention on common global threats to humankind, e.g., global warming, ozone depletion, and, of course, the threat of NEO impacts. The proposed quick asteroid rendezvous mission would allow interested nations to begin the process of learning how to solve the NEO impact hazard through multinational multidisciplinary teaming and cooperation. Conducting such a mission would also allow various scientific disciplines the opportunity to learn more about NEOs and the role they have played in the origin and evolution of our solar system and Earth and the dynamics of the current space debris environment.

What we would learn

There are a number of things we would learn by conducting this specific asteroid rendezvous mission. In the area of impact threat detection we would be creating added emphasis for astronomers and military observers to spot, track, and catalog near-Earth objects. In the case of a promising candidate NEO detected to be on a close-approach trajectory to Earth, we could then exercise a worldwide network to provide warning to all concerned. In the area of scientific discovery we would all be richer because of the increased understanding of small NEOs which would result. We would be able to learn more about their composition and structure; their cratering record; and perhaps even insights into how they were formed. With regard to mitigation, or actual defense of the planet, we'd first and foremost learn about how to conduct a mitigation mission, which is no easy undertaking (Tedeschi, 1994). More specifically, we'd learn how to do planning, build smart maneuverable spacecraft payloads, survive the harsh environments of space, acquire the rapidly approaching NEO target, do terminal homing, impact the target or deposit the mitigation technology in some stand-off mode of energy deposition, and deposit energy and create a useful deflection or fragmentation response in the NEO. Perhaps most importantly we would learn more about international teaming and cooperation to solve this long-term, albeit low probability - but high consequence, threat to humankind.

Asteroid targets of opportunity

Using existing Earth-impacting NEO fluxes (Morrison, 1992 and Tedeschi, 1994), we estimated to first-order the NEO flux in the near vicinity of Earth (within the Moon's orbit and reachable by rockets in a short period of time) by simply ratioing the cross-sectional area of some window of rendezvous opportunity to the cross-sectional area of Earth. For this example, we assumed a window of rendezvous opportunity of radius 120,000 km from the center of

Earth. The estimated flux of NEOs through this window of opportunity compared to the Earth-impact flux is shown in Fig. 1. As can be seen, there are perhaps a few dozens of rendezvous opportunities each year of 5-10 m diameter-sized NEOs passing within this window. Of course, warning of their approach would have to be timely to allow launch preparations, mission planning, launch of a rendezvous spacecraft, and transit time to the approaching NEO. Approximately 24-30 hours minimum warning would be needed, although current warning times are less than this, approximately 1/2-day (Scotti et al., 1991 and Gehrels, 1995) for this class of NEOs. So the NEO rendezvous targets of opportunity exist, what remains is to enlist the astronomers to detect and provide early warning of their approach.

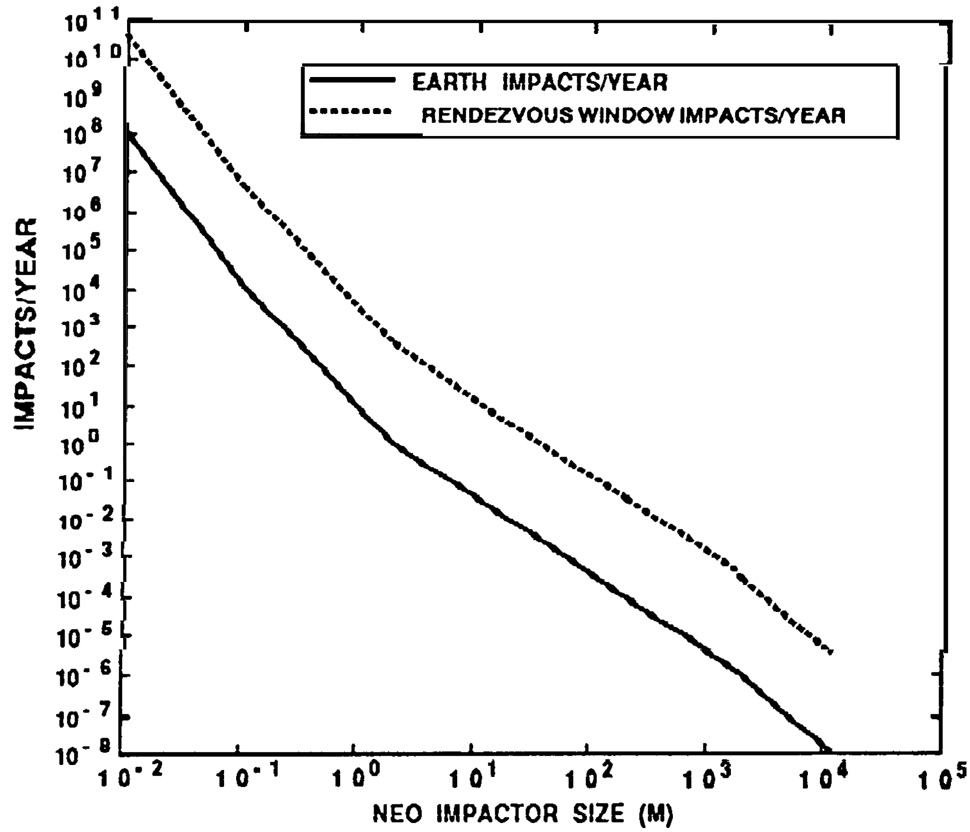

Figure 1. NEO impact flux comparison to Earth versus a 120,000 km window of rendezvous opportunity centered about the Earth.

Astronomers provide early warning

Early warning of a close-approaching asteroid would be provided by a world-wide network of electronically connected astronomers and military observation sites. The Internet could be used effectively to alert others of an apparent close-approach NEO discovery. The current approach for reporting new NEO discoveries to the IAU's Minor Planet Center appears to be a good model for a central clearinghouse to receive and disseminate information. Other existing rapid communication systems might also be used. Other observers in the approaching nighttime sector would then follow-up with optical and radar tracking to obtain a more accurate trajectory assessment. The very initial early warning would also allow the launch site to begin preparations for launch. Ground-based telescopes (see Fig. 2) would be used for the initial detection of approaching NEOs, with follow-up astrometric tracking provided by ground-based radars (see Fig. 3). The example NEO used in this study was the December 9, 1994 asteroid XM1 discovery by the University of Arizona Spacewatch group (Gehrels, 1995). An Apollo (carbonaceous) asteroid estimated to be 6-13 m in size and 30 km/sec in relative approach velocity passed within 105,000 km of Earth. It was detected only about 12 hours before closest approach. Using this as the target we sized an approximate mission (timeline, trajectory, and spacecraft) to rendezvous with the target in about one day's time.

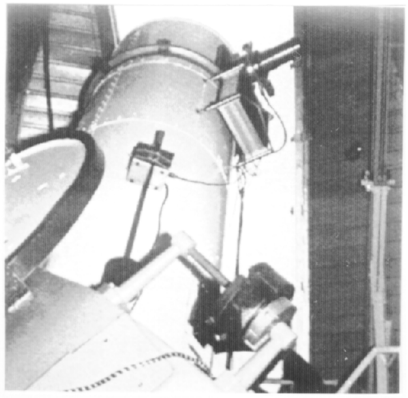

Figure 2. Spacewatch 0.9 m scanning CCD telescope.

Figure 3. NASA-JPL 70 m deep-space Goldstone radar.

Use a solid rocket booster with a smart rendezvous package

It is proposed for discussion purposes that the Russian Start 1 (SS-25) booster (see Fig. 4) be used as the launcher for a specially designed and built spacecraft, the front of which could be the smart and small LEAP rendezvous package (see Fig. 5). The Russian Start 1 rocket is being developed as a low-cost, low-end commercial spacecraft launcher (Covault, 1995). Once fully developed, its 4 stages are estimated to have the ability to place a 370 kg payload into a 500 km, low-inclination Low-Earth Orbit (LEO). We selected this booster because of its relatively low $/kg LEO delivery capability. The spacecraft payload would consist of an orbit transfer motor (to go from LEO to a rendezvous trajectory), an observer package (with scientific instruments), and the LEAP vehicle.

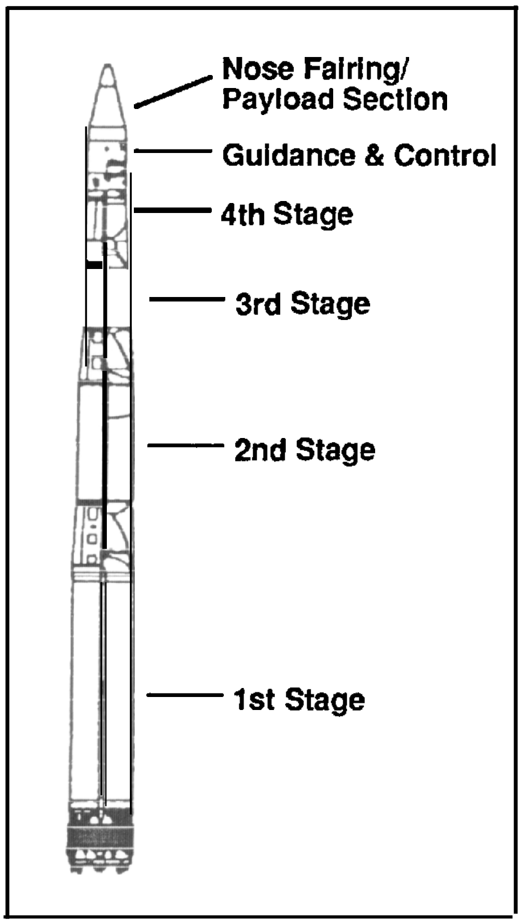

Figure 4. Russian Start 1 Launcher.

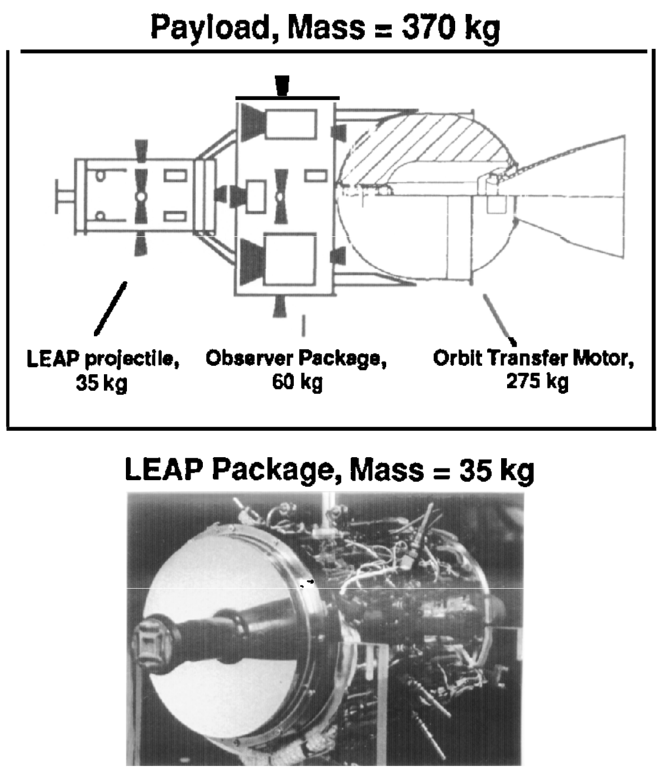

Figure 5. Spacecraft payload diagram and LEAP.

Launch preparations, flyout trajectory and rendezvous location

The launch site would be notified as early as possible of an approaching NEO rendezvous target of opportunity. Because of the short timelines, the amount of prep time for the launcher and payload could be as short as 4 - 8 hours, thereby necessitating maximum payload readiness at all times. This would undoubtedly require on-site technicians to check the payload and booster every few days or so during the perhaps 2 - 4 month wait for a NEO target of opportunity. Once the warning is received, a final check-out of the payload subsystems states-of-health would be made, followed by mating with the booster (or it may already have been mated with the booster), assent shroud attachment, and preparations for launch. The complete rendezvous mission profile would also have to be calculated on-site and then loaded into the booster as part of the preparation phase. The launch should be done from a low latitude ($< \approx 30°$) site, such as either Kourou, French Guiana (5.5° N) or Cape Canaveral (28.5° N), to take advantage of maximizing on-orbit payload insertion mass due to the velocity assist provided by the Earth's eastward rotation (Isakowitz, 1991 and Wertz and Larson, 1991). Insertion into a LEO parking orbit would occur approximately 15 minutes after launch, followed by perhaps 1 - 2 hours for on-orbit spacecraft check-up. While in LEO, we would also want to refine the rendezvous trajectory mission profile in the onboard G&C computer, based on updated trajectory parameters supplied by the net of astronomers tracking the NEO. At the precise time, the orbit transfer motor (in this case a Thiokol Star 26 motor; 271.7 sec ISP, 270 kg mass, 7,800 lbf avg. thrust, and 91% propellant mass fraction) would be ignited to give the spacecraft a ΔV of 2.93 km/sec into a Hohmann transfer orbit (see Fig. 6) with a 105,000 km apogee. For this example, rendezvous with the approaching NEO would occur 18 hours later. The orbit would be posi-grade so that basically the spacecraft would be near apogee at the time of rendezvous. The payload would be in front of the approaching NEO and would use its lateral divert capability to maneuver itself such that the NEO would hit it from behind. Of course, it's possible to have a quicker, more direct assent to the NEO rendezvous location, but at the expense of less payload or a larger booster.

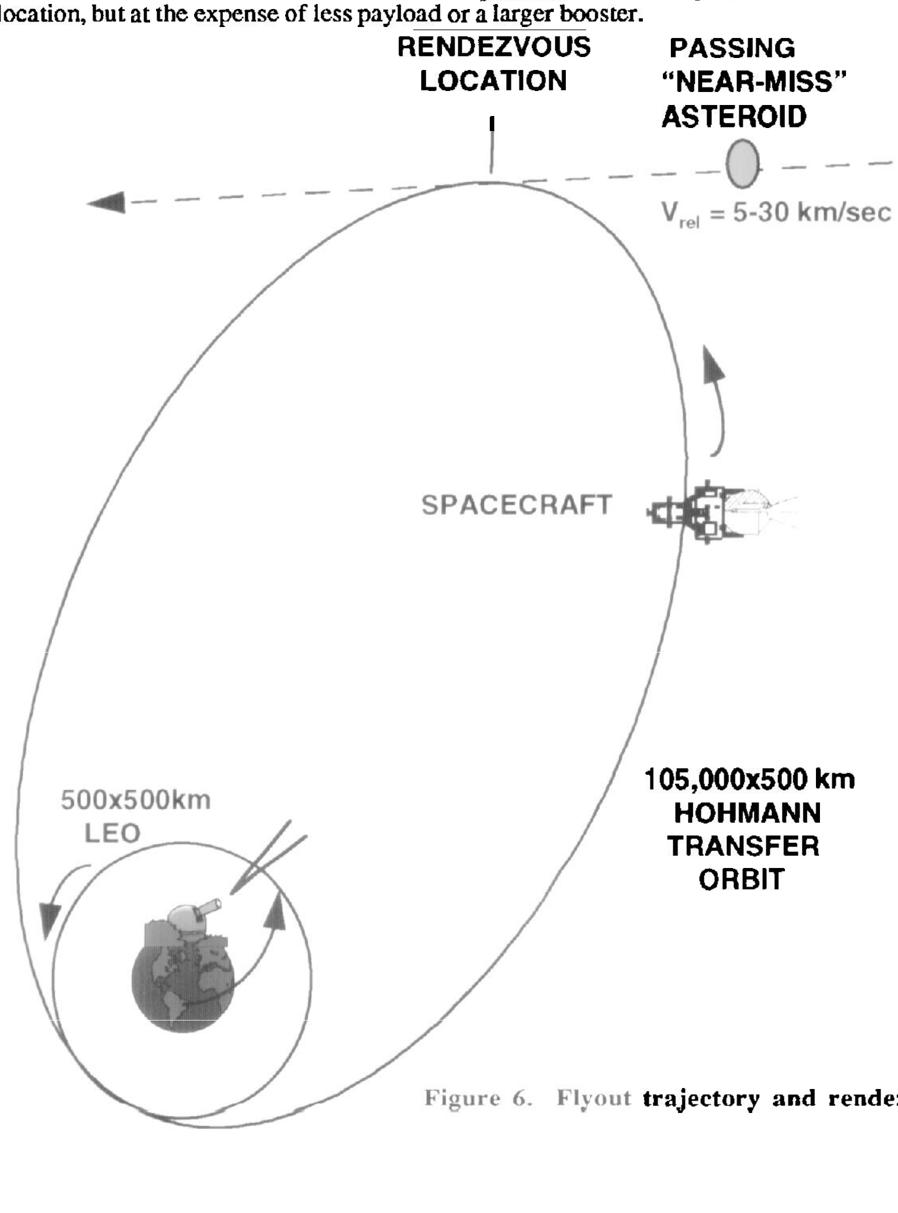

Figure 6. Flyout trajectory and rendezvous location.

Data collection

Observations of the asteroid rendezvous would be made by two principle means; the space-based penetrator and observer packages, and the ground-based instruments. Proposed space-based sensors on the two spacecraft packages are shown in Fig. 7. The exact sensor mix is, of course, subject to further mission planning and sensor availability. Ground-based world-wide assets would include: telescopes (optical, UV, and IR - broadband and discrete spectral coverage), radar (for tracking the spacecraft and NEO target beforehand and measuring target momentum change and debris cloud characteristics after the rendezvous), and telemetry collection of the data transmitted from the space-based assets (from the two spacecraft and in the 1-10 GHz range).

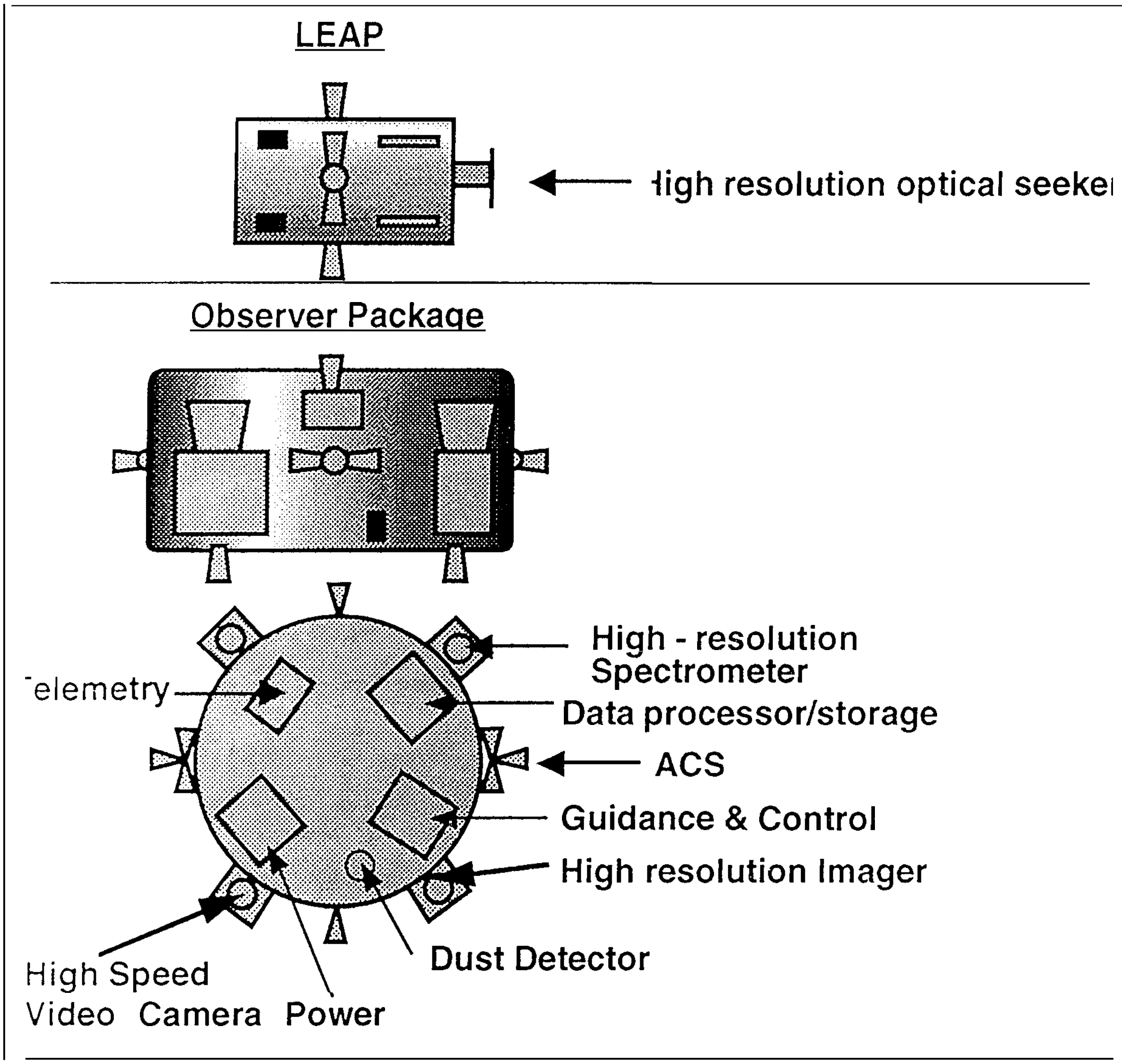

Figure 7. LEAP and Observer Package sensor suite.

Asteroid rendezvous - target penetration

The primary rendezvous mission would involve penetration of the target NEO by the LEAP vehicle (see Fig. 8), with the observer package watching the penetration from about 1 km away. The LEAP vehicle would separate from the observer package minutes before closest approach and then use its lateral divert capability to perform final homing on the rapidly approaching NEO. The observer package needs to be removed from the direct vicinity of the NEO because of the debris field the impact will create, so as to maximize data collection by the observer package.

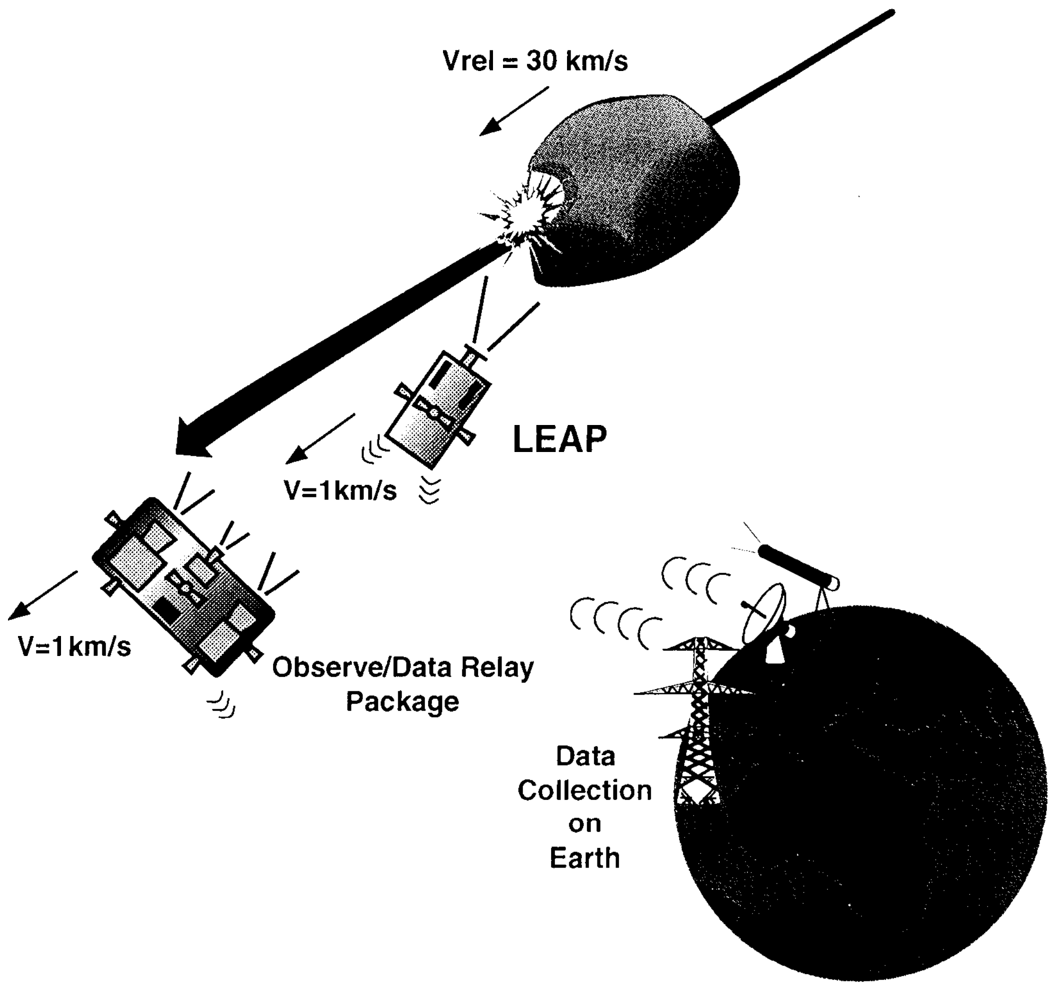

Figure 8. Impact of the target NEO by the LEAP package, with the observer spacecraft nearby, and data collection on Earth.

Data analysis and interpretation - penetration mission

For a successful asteroid rendezvous penetration mission, there would be many sources of data for subsequent analysis and interpretation (see Fig. 9).

DATA ANALYSIS ACTIVITY	INTERPRETATION
Spectral Data	Elemental and molecular composition of the asteroid along the penetration shotline.
Impact Flash Data	Increased understanding of the impact physics.
Radar Data	Initial body dynamics; Level of momentum deposition (trajectory alteration) and/or creation and trajectory of a fragmentation debris cloud.
Dust Detector Data	Increased understanding of the impact physics.
High-Resolution Images	Shape and surface texture; Cratering record; Clues to the origin of the body

Figure 9. Data to be derived from the impact mission and possible interpretations.

Simulations of the interaction of the LEAP penetrator with a 5-meter class NEO body (see Fig. 10) were performed with the Smoothed Particle Hydrodynamics (SPH) model (Libersky et al., 1991 and Luehr and Allahdadi, 1994). Interesting features in these calculations are: 1) the projectile penetrated only about one body length into the target and subsequently coupled all its kinetic energy into the NEO material - typical for a HV impact, 2) a massive crater has formed in the target after just 1 microsecond, and 3) the target may possibly fragment as a result of the impact.

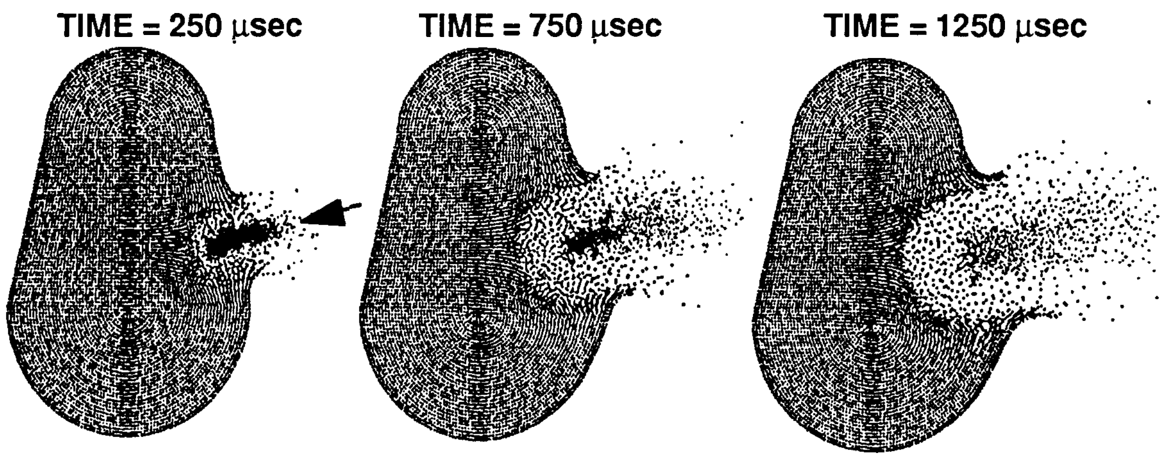

Figure 10. Hypervelocity impact simulation using the SPH code of the LEAP penetrator impacting a 4 by 7 m rock NEO target at 30 km/sec.

Of concern from a safety perspective would be the resultant debris cloud if the target NEO were to catastrophically fragment due to the LEAP package impact. Using existing breakup models (McKnight, 1991), Figure 11 gives estimated parameters for the debris cloud produced by the 35 kg LEAP penetrator impacting the 4 by 7 m sized NEO shown in Figure 10. Obviously an extremely energetic and well-populated debris cloud is created. Range safety would therefor dictate that the rendezvous mission parameters be such that any resultant debris cloud be directed away from Earth or that a larger NEO target be sought where the expectation of catastrophic fragmentation is remote, i.e., the projectile energy to target mass ratio is well below the fragmentation threshold of about 3 - 10 J/gm (Tedeschi, 1995), versus 56 J/gm for the estimation made above.

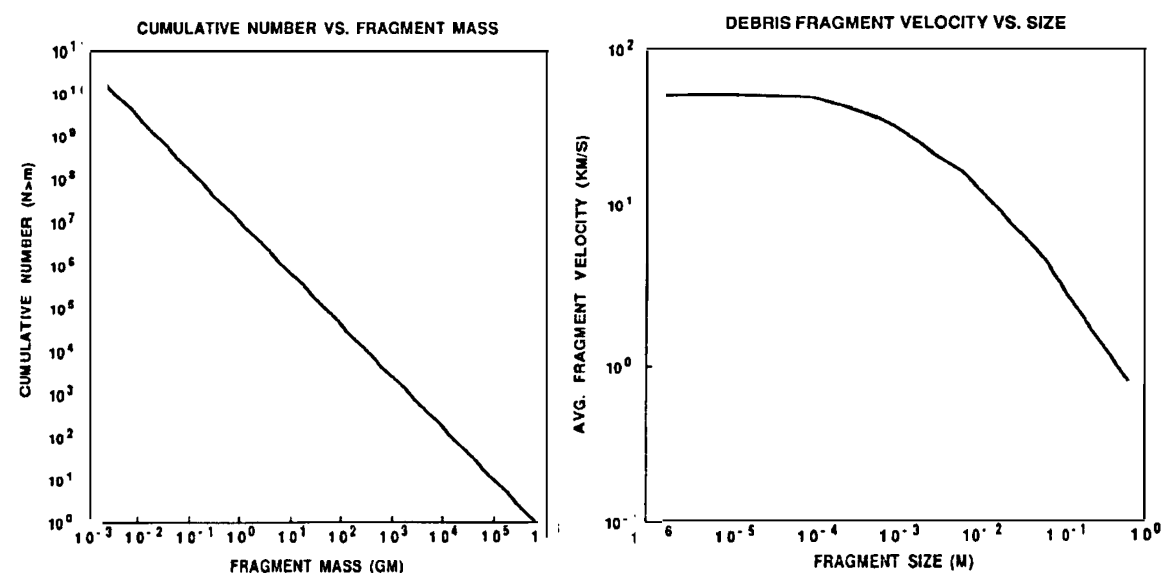

Figure 11. Estimated debris cloud characteristics for the 4 by 7 m target NEO impacted by the LEAP penetrator.

Fast Flyby asteroid rendezvous/data analysis and interpretation

Should the primary mission objective of a target penetration not be achieved, then for the case of a near-miss we would still have a fast flyby mission, from which much could still be learned. Many sources of data would still be available for subsequent analysis (see Fig. 12) and interpretation (see Fig. 13).

DATA ANALYSIS ACTIVITY	INTERPRETATION
Spectral Data	Molecular composition of the asteroid's surface.
Radar Data	Body dynamics and trajectory.
Dust Detector Data	Presence of nearby particulates.
High-Resolution Images	Shape and surface texture; Cratering record; Clues to the origin of the body.

Figure 12. Data to be derived from the fast flyby mission and possible interpretations.

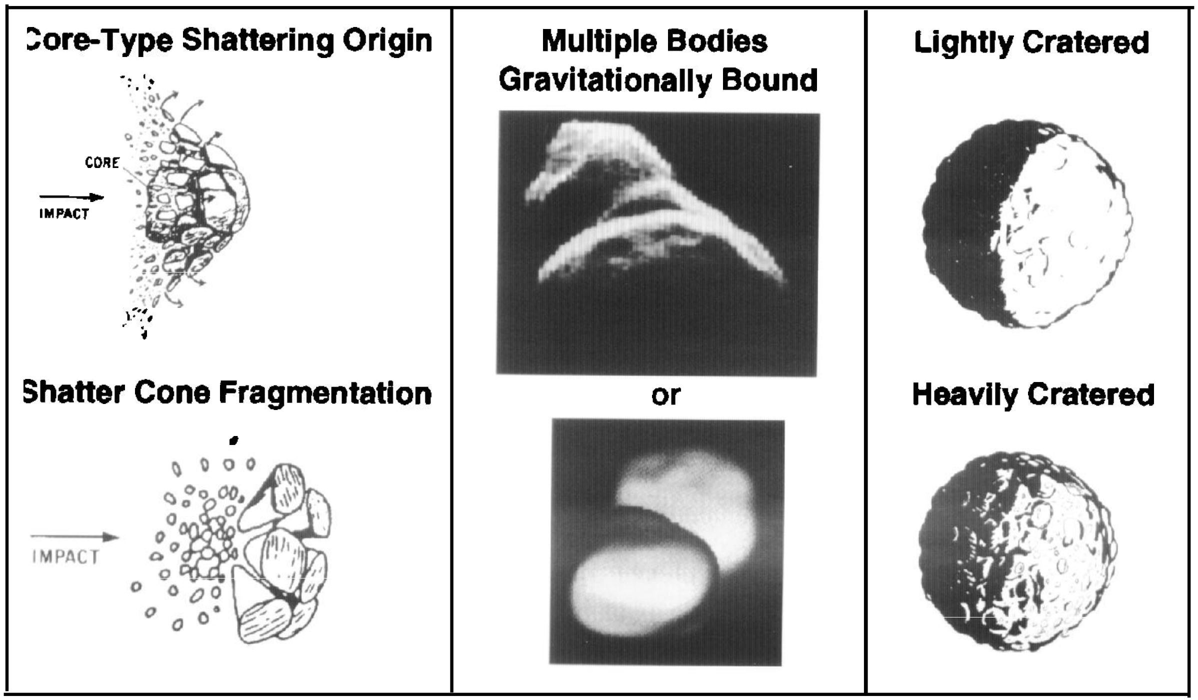

Figure 13. Possible conceptual interpretations from a fast flyby mission.

International participation and cost

It is recommended that the proposed asteroid rendezvous mission be a joint one between many nations. We all are stakeholders in the consequences of massive NEO impacts on Earth, we should all therefore consider working together to understand the problem and generate reasonable and acceptable solutions for the protection of life on Earth against NEO impacts. Figure 14 is a preliminary and most certainly incomplete listing of possible members of an asteroid rendezvous team and their potential contributions. As this proposed mission, and others like it (Nozette, 1995), are discussed in the coming years, many changes will undoubtedly be made to the list below before the mission team, investigators, and contributions are set. Initial cost estimates are for the total mission to cost approximately \$15M using almost exclusively off-the-shelf hardware and existing worldwide space assets (sensors, hardware, facilities, and other capabilities). Each nation must be willing to provide resources, assets, and capabilities to make this proposed mission a success.

WHO	WHAT
Chinese	Sensors, mission services, analysis
DOE National Labs	Analyses/Data Interpretation Observer Package Design & Integration
Europeans (ESA)	Dust Sensors, planning, mission services
International Scientists	Principle Investigators, data interpretation
Japanese	Observer package sensors, mission services
NASA	Sensors, planning, mission services
Russians	High-energy impact physics, sensors Start Rocket, launch integration
USAF Phillips Laboratory	LEAP Penetrator Impact Response/Data Interpretation
USAF Space Command	Mission planning, launch & mission services, systems integration

Figure 14. Possible asteroid rendezvous mission team members and contributions.

Summary

Kinetic energy is a viable mitigation technique to protect Earth from the NEO impact hazard under certain circumstances by either deflecting or disrupting an approaching body. However, for us to have confidence in the effectiveness of kinetic energy as a defensive capability, we have proposed for broad consideration the conduct of a quick and relatively inexpensive (albeit high risk) asteroid rendezvous mission. Doing so would result in many benefits, not only would it increase our scientific understanding of NEOs, but it would also allow us to better understand and model the delivery and deposition of kinetic energy into NEO targets and their resultant response, i.e., cratering and deflection, or fragmentation. Conducting low-cost space experiments now is more likely to allow timely and effective defensive responses in the future.

Acknowledgments

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